machining parameters showed 5 percent scatter in dimensional instability, but all were within the required tolerance band.

3.2 Validation on Compressor Disc. Effect of optimal machining parameters on dimensional instability in compressor discs is shown in Fig. 1. The locating diameter 400 (+0.02/0.00) mm was machined using the optimal machining parameters derived for 11–20 micron tolerance group. The diameter maintained at 400 (+0.010/0.00) mm during machining has changed to 400 (+0.015/0.00) mm after 360 hours. This change in dimension is within the acceptable tolerance band.

4 Conclusion

1 Empirical equations for predicting surface residual stresses, dimensional instability, surface finish and tool life were derived by response surface methodology.

2 Experimental results have shown that residual stresses and dimensional instability are highly correlated. Therefore, dimensional instability, tool life, surface finish and material removal rate were considered for optimization.

3 A simultaneous optimization method based on desirability function approach was used. The optimal cutting parameters are derived to control dimensional instability within 11–20, 21–30 and 31–50 micron tolerance bands in turning precision aero gas turbine engine components made of Inconel 718.

4 Dimensional instability was within the acceptable tolerance band for the test specimen and actual jet engine components that are machined with optimal machining parameters obtained by simultaneous optimization.

Nomenclature

α = rake angle, deg.
b_i, b_{ij} = regression coefficients
$\{\mathbf{B}\}$ = vector of regression coefficients
C_r = rake angle correction factor
C_l = chip thickness correction factor
d = depth of cut, mm
d_1 = desirability of tool life
d_2 = desirability of material removal rate
d_3 = desirability of dimensional instability
d_4 = desirability of surface roughness
D = composite desirability
$DIMI$ = dimensional instability, μm
$DIMI_c$ = most desirable dimensional instability, μm
E = transmission efficiency of the drive
f = feed, mm/rev
ID = inner diameter, mm
MRR = metal removal rate, mm^3/min
OD = outer diameter, mm
p = power per unit metal removal rate, W/mm^3/min
P_m = lathe motor power, W
r = tool nose radius, mm
R_a = surface finish, μm
σ_c = circumferential residual stress MPa
σ_l = longitudinal residual stress MPa
T = tool life, min
ν = cutting speed, m/min
x_1 = coded value for ν
x_2 = coded value for f
x_3 = coded value for d
x_4 = coded value for α
x_5 = coded value for r
X = matrix of coded variables
X' = transpose of X
y = estimated response
$\{Y\}$ = vector of measured responses

Subscripts

max = indicates maximum value
min = indicates minimum value

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Edge Radius Variability and Force Measurement Considerations

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A new, noncontact instrument, based on white light interferometry, is used to measure the edge radii of cutting tools with measurement errors of less than 3 μm. Edges of several commercial cutting inserts are measured and compared. It is found that the radius of the hone varies along the length of the edge in a parabolic manner. The difference between the edge radius at the center of the edge and the radius at the start of the corner can be as large as 25 μm (0.001 in). The variation between the edges on an insert and across inserts in a batch of tools can be as high as 25 μm (0.001 in). Statistically significant variations are also seen in the corner radius region in which much cutting occurs in turning, boring and face milling processes. Orthogonal cutting tests with tools of measured edge radius in the zone of cut indicate that the machining forces, especially the thrust force component, are sensitive to changes in edge radius on the order of measured variations. [S1087-1357(00)01603-8]

Introduction

Edge hones are commonly used as an edge preparation in many operations, like interrupted cutting, machining of hard materials, etc., where increased edge strength is desired. Edge hones in the

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range of 75 μm (0.003 in) to 125 μm (0.005 in) are commercially available for heavy duty machining of hardened steels (>35 Rc) and cast irons. The edge preparations on commercially available inserts are generally prescribed as a range. For example, edge preparation *A* is specified to have a hone ranging from 10 μm (0.0005 in) to 80 μm (0.003 in). Two of the processes that are commonly used to obtain edge hones are honing by nylon brushes impregnated with silicon carbide, and honing by abrasive entrainment in an air-stream. In the brush honing process considered here, cutting edges are polished when the inserts, mounted on a rotary carrier, are slowly rotated about their inscribed-circle axis while being fed through the rotating brushes. By varying the time and depth of contact between the brush and the cutting edge, different edge hones can be obtained. The variation of an edge feature from its nominal value, both along an edge and edge-to-edge, is not well understood. Large tolerances on the edge hone could lead to significant variations in machining forces when cutting with different inserts of the same nominal specification. The aim of the reported work is to study edge hone variability on commercial inserts and the relative effects on machining forces and model calibration data. It is *not* the aim of this paper to *model* the effects of the edge radius on the cutting process, nor is it to model the brush honing process.

Edge Radius Measurements

Accurate measurement of the edge radius is a fairly difficult task that has been addressed in some detail in only a few studies [1,2]. In this study, we describe the use of a new optical technique based on white light interferometry (see Sasmor and Caber [3] for a detailed review of optical measurement techniques). The WYKO™ measurement system used here, which is based on the physics of white light phase-shift interferometry, combines accurate optics, axis movement and a computational software interface to make measurements with vertical resolution as good as 2 nm (0.002 μm) [4].

Three sets of TPG432 uncoated carbide inserts (sets *A*, *B* and *C*) were requested from a vendor to have corresponding nominal edge radii (specified at the center of the edge) of 50.8 μm (0.002 in), 100.6 μm (0.004 in) and 152.4 μm (0.006 in). After going through quality checks at the vendor's facility, the inserts were measured independently by the research team. Care was taken to reduce sources of measurement errors. A small fixture that held the insert at the proper (and constant) orientation relative to the optics of the system, together with an automated positioning table, ensured that measurements on different inserts and edges were at identical locations along the edge. Repeatability tests showed that the estimated profiles were within 50 nm (0.05 μm) of each other. Details of scan data processing are given in [5].

Variability Between Edges and Inserts. Eight inserts from each set were chosen to evaluate the variability across edges and inserts. Comparing the nominal specifications to the measured data indicated that the edge-center-point means were smaller than the prescribed nominal values, in this case by about 15 μm (0.0007 in) for the sets *A* and *B*, and by about 5 μm (0.0002 in) for set *C*. This would indicate that it is difficult to manufacture the inserts to a tight tolerance on the mean for tools with a smaller edge radius (within 35 percent of the nominal for set *A* as compared to within 3 percent for set *C*). The variation about the mean is about 6 μm (0.00025 in) for sets *A* and *B*, and 14 μm (0.0005 in) for set *C*, which is approximately 10 percent of the nominal values for all sets. Only 50 percent of the measured values were in a range of 10 μm (0.0004 in) for sets *A* and *B*, and 25 μm (0.001 in) for set *C*.

A general nested linear analysis of variance was conducted in which the edge radius was modeled as equal to a tool effect plus a nested effect of edge on tool. It was found that both these variables were statistically significant at a *P*-level of 0.024 on tool and 0.014 on edge (both of set *B*). Sets *A* and *C* were significant at even smaller *P*-values. In other words, between inserts there existed a significant shift in insert mean (the average of the edge-center-point measurements on each of the three edges of an insert) and, furthermore, there existed an edge-to-edge mean shift on each insert.

Placing 95 percent confidence bands on the insert means for nine inserts of set *A* demonstrated that if an insert with nominal edge radius of 50.8 μm (0.002 in) is procured commercially, the actual edge radius at a specified point on the edge could be off by as much as 22 μm (0.0009 in). This error is perhaps indicative of why most manufacturers specify the edge preparations in ranges of values.

Variability Along an Edge. The second important issue to investigate is whether or not the location along the cutting edge affects the edge radius in a statistically significant manner. Two inserts from every set were chosen and measurements were made on four of the six edges at five zones on each edge corresponding to 7.8 mm, 5.2 mm, 0.7 mm, −3.4 mm and −6.7 mm from the center of the edge. These points were chosen such that one point corresponded approximately to the center of the edge with the other points distributed on either side. Using the automated positioning table, the locations of these positions were maintained to be the same for all the measured edges. The variation of edge radius along the edge is shown in Fig. 1. It is obvious that the edge radius at the center of the edge is consistently lower as compared to the radius at points closer to the corner (7.8 mm and −6.7 mm locations). The R^2 values for the individual fits were about 60 percent. Analysis of variance showed that edge location indeed was a significant factor. It also showed that the edge-number label was insignificant.

Variability Around Insert Corner. While variability along the straight portion of an insert edge may impact straight-edged orthogonal cutting tests, most real-world applications of cutting inserts involve cutting, at least in part, on the corner radius of the insert. Therefore, force prediction models being developed for such applications, which extend the models being formulated for straight-edged orthogonal cutting, should account for edge radius variation around the corner, if it exists. With this in mind, the edge radius around the corner was measured on several inserts from set *A* to evaluate the relative variation in the corner region as compared to the straight lead-edge region studied above.

A fixture was fabricated to permit three measurements on each corner—one at each of the two tangent points where the corner meets the two straight edges, and one at the apex of the corner. The statistical model employed to analyze these data was a general linear model with the corners as nested within insert for the same reason edge number was nested within insert in the earlier analysis. The two possible two-factor interactions were also

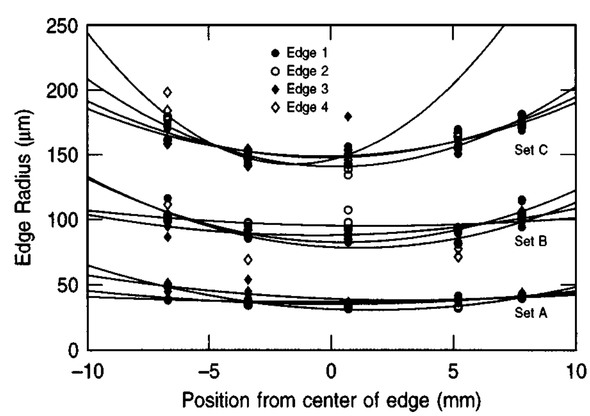

Fig. 1 The variation of edge radius along the four cutting edges of inserts from set *A* (50.8 μm (0.002 in)), set *B* (101.6 μm (0.004 in)), and set *C* (152.4 μm (0.006 in))

evaluated in this model. Results of the statistical evaluation show insert and position to be statistically significant, at *P*-values of 0.035 and 0.009, respectively, and corner(insert) as well as the two interactions to be insignificant. This reveals that the edge radius does vary with position around any given corner and furthermore that there is a difference between inserts, although variation between corners of a single insert is statistically indistinguishable from random errors.

Force Measurement Considerations

Orthogonal cutting experiments were conducted on a J & L CNC lathe by end cutting of tubes of three materials: gray cast iron, 2024 aluminum and commercially pure zinc. A wall thickness equal to 4.83 mm (0.19 in) was used to maintain plane strain conditions. A Kistler piezoelectric dynamometer was used to monitor three machining force components. To reduce the variation of the edge radius along the width of cut, which could lead to misleading force measurements, all the cutting tests were performed at the center of the edge where the edge radius had been measured prior to the experiment and where the variation gradient is lowest across the width of cut. It can be seen from Fig. 1 that the maximum variation in edge radius across a 5 mm (0.2 in) width of cut that is equally distributed about the edge center-point is only about 6 μm (0.0004 in) for inserts from set *C*.

Each material was cut at several feeds by two inserts whose hones were described by the vendor as 50 μm (0.002 in) and 100 μm (0.004 in). Since the significance of the effect of the edge radius increases at smaller uncut chip thickness, feeds were selected such that the ratio of uncut chip thickness to edge radius (h/r_n) varied between 0.5 and 5. This represents the range commonly seen in the operations of practical interest (hard turning and finishing operations). The edge radius effects seen here would be more pronounced at even lower uncut chip thicknesses.

Graphs of the cutting and thrust forces (normalized by the width of cut) versus the uncut chip thickness *h*, for all three materials, are presented in Figs. 2 and 3. As expected, the effect of the edge radius is visibly larger on the thrust force than on the cutting force. It can be seen that intercepts (a qualitative measure of edge/ploughing contributions) are higher when the materials are being cut with tools of higher edge radius. Even for zinc where the edge radius effect seems to be quite small, 95 percent confidence bands on the force measurements lie far apart (band-to-band separation of 2.5 to 3 times the confidence bands), which statistically supports the significance of the edge radius effect on the forces. If it is assumed that there is a linear variation of machining forces with edge radius, then it can be shown that the predicted force for an insert with edge radius of 75.6 μm (0.003 in) would lie well between the confidence bands of sets *A* and *B*.

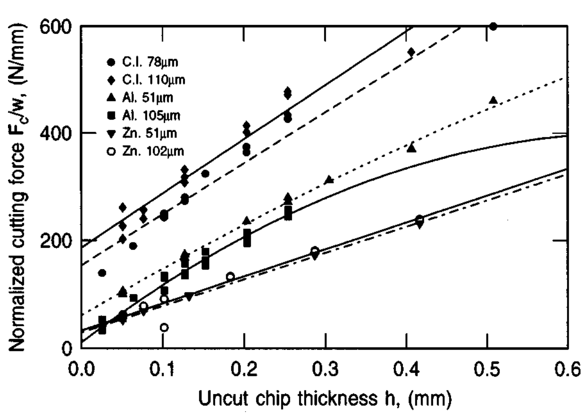

Fig. 2 Variation of the cutting force component with uncut chip thickness for cast iron, aluminum and zinc at various edge radii

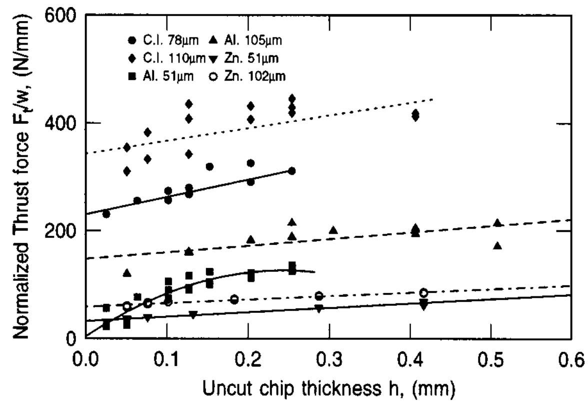

Fig. 3 Variation of the thrust force component with uncut chip thickness for cast iron, aluminum and zinc at various edge radii

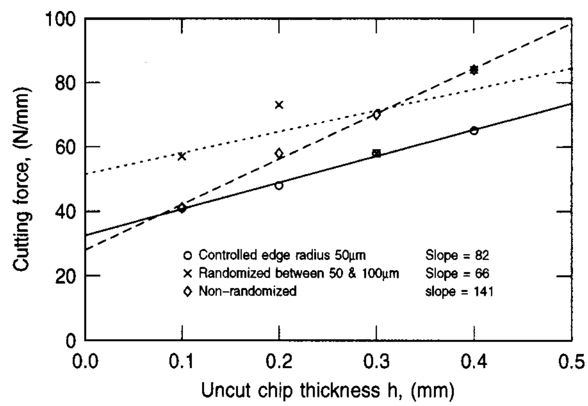

Fig. 4 Increased errors observed when different parts of the cutting edge are used for calibration testing

This proves that the increase in forces are of a higher order than the experimental error in the force measurements.

The variability along an edge raises an important consequence regarding force measurements made for force model calibration via straight-edged orthogonal cutting tests. If the machining forces are assumed to have some portion that is proportional to the edge radius, then the machining force must vary parabolically along the length of the cutting edge. Arbitrary or randomized selection of zones along the cutting edge will result in measurement of machining forces that appear to exhibit noise. Machining force data is meaningful only when all the tests are run with tools of the same edge radius. In Fig. 4, cutting forces that were predicted using a simple force model, based on data collected here, are shown for three situations—controlled tests in which a single edge radius is used, randomized tests along the cutting edge, and nonrandomized tests. It can be seen that randomized and nonrandomized tests lead to lower R^2 values and, more importantly, an incorrect slope and/or intercept. Hence, we can conclusively state that it is important to measure and maintain the edge radius at the cutting zone in order to obtain accurate force data.

Conclusions

It was shown that there is a statistically significant parabolic variation of edge radius along a cutting edge, which is presumably due to the geometry of the brush honing process. Statistically significant variation of the edge-center-point mean across edges and inserts (about 25 μm) was also observed, which is attributed to the difficulty of controlling the honing process. Variation was observed in the corner radius region as well, being statistically significant around the corner and from insert to insert. It was also shown that the machining force components are sensitive to changes in edge radius on the order of the measured edge variation. This machining force sensitivity is of a higher order than experimental error (noise) in the measurement of forces. Hence, accurate prediction of force magnitude and direction, for honed tools, may likely require consideration of hone variation around the corner and along the lead edge. Furthermore, care must be taken to avoid introducing hone variation by changing edges or adjusting the cutting-zone location along the edge when conducting cutting tests, which is a typical approach to avoiding excessive wear evolution over the duration of a set of tests.

This study also further supports the fact that edge radius plays an important role in process mechanics, particularly at conditions of low h/r_n. Work that addresses the effects of the edge radius on the cutting process and the development of a cutting model that alleviates the sharp tool assumption are in progress.

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